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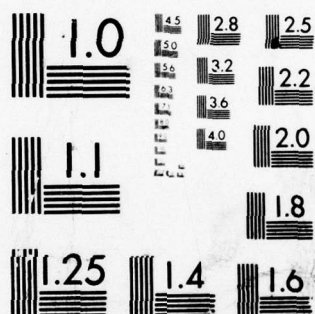
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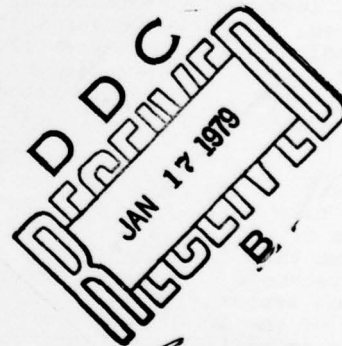
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Experimental Techniques Applicable to Turbulent Flows

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EXPERIMENTAL TECHNIQUES APPLICABLE TO TURBULENT FLOWS

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Abstract

The recently developed Laser Raman and Laser Doppler techniques may be ideally suited for the diagnostics of combustion. Both techniques are nonintrusive and essentially supplementary. However, under certain conditions the spontaneous Raman diagnostics may fail, due to excessive noise, unwanted fluorescence and other sources of interference. In order to alleviate these difficulties, an attempt has been made to use the CARS diagnostic method. In this paper, after a review of the above-mentioned diagnostic techniques, some experimental results, and some data processing methods are discussed, which permit the extraction of turbulent information from spontaneous Raman scattering. These are compared to turbulent data as obtained from L.D.V..

I.   Introduction

As a result of the energy crisis, and the fact that almost all of the energy derived from fossil fuels is obtained as a product of a combustion process, the interest in the detailed understanding of the phenomena involved in combustion, has been revitalized. It became clear that a better understanding of the processes involved is vital not only for more efficient designs of the combustors, with the associated savings in precious fuels, but from the environmental point of view, it could provide an answer to the problem of protecting the environment by a reduction or a possible elimination of the harmful exhaust emissions of combustion systems. It is well known that contrary to the highly developed technology in practical design of combustion systems, a scientific understanding of the details of the combustion processes is still in its infancy. However, recent investigations and exchanges of views in the scientific community (Ref. 1,2,3,4,5) have contributed greatly to a systematic definition of the problems and delineation of some particular aspects of combustion which appear to be of major importance in reaching a detailed understanding of the phenomena involved. It has been found that a phenomenon exerting a great deal of influence on the combustion processes is turbulence. A knowledge of the turbulence level, instantaneous temperature and concentration of the species involved may be very useful in understanding the combustion process. Modern developments in nonintrusive laser diagnostic techniques of flow fields could be of significant value in this context, if applicable to combustion processes. In this paper an attempt is being made to determine simultaneously the concentration of several species of interest in a flame, their individual temperatures as well as the turbulence intensity. The concentration and temperature is obtained using the spontaneous Raman effect, and the turbulent intensity by means of a L.D.V. using the concentration and temperature data, an attempt will be made to extract the flucuation intensity and compare it with the intensity as obtained using the L.D.V. techniques. Furthermore, some data concerning specie concentration in a flame are discussed using the coherent antistokes Raman scattering method which, in spite of some disadvantages as compared to the spontaneous Raman effect, may be of major importance in applications concerning combustion.

II.   The Raman Effect

The Raman Effect[6,7,8,9,10] is the phenomenon of light scattering from a material medium, whereby the light undergoes a wavelength change and the scattering molecules an energy change in the scattering process. The Raman scattered light has no phase relationship with the incident radiation. The Raman shifts correspond to energy differences between discrete stationary states of the scattering system. Classically, the Raman Effect can be described as the modulation of the scattered light by the internal motions of the scattering molecules. In this kind of analogy, the Raman lines would correspond to the side bands, and the Rayleigh light to the carrier frequency. This, of course, would result in the Stokes and Anti-Stokes lines having the same intensity, which is not the case. Quantum theoretically, the incident photons collide elastically or inelastically with the molecules to give Rayleigh and Raman lines, respectively, with the inelastic process much less probable than the elastic. When an inelastic collision occurs with the incident photon furnishing energy to the molecule raising it to a higher energy level, the scattered photon being of lower energy, gives rise to the Stokes line. If the scattering molecule gives up energy to the impinging photon and moves to a lower energy state, the scattered photon gives rise to the Anti-Stokes line. Since the Anti-Stokes line must originate in molecules of higher energy level, which are less abundant at normal temperatures, the Anti-Stokes lines would be expected to be much weaker than the Stokes lines. The process of light scattering can thus be visualized, as the absorption of an incident photon of energy E by a molecule of a given ini-

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tial state, raising the molecule to a "virtual" state, from which it immediately returns to a final stationary state emitting a photon of the difference energy between the two states and incident energy E. The process is illustrated in Figure 1.

This general qualitative behavior, holds for the vibrational as well as rotational transitions, with the appropriate selection rules, which tend to limit what appeared to be an extremely large number of possible transitions and consequently large number of Raman lines.

Since for the purpose of this work the vibrational Raman scattering is of direct interest, it is worthwhile to examine the vibrational Raman response. It consists essentially of three branches:

a) The intense Q branch for which $\Delta J = 0$
b) The much weaker O branch for which $\Delta J = -2$
c) The much weaker S branch for which $\Delta J = +2$ of the same intensity as the O branch.

It can be shown that only about 1% of the total vibrational intensity resides in the O and S branches and as such is of minor importance as far as the present application is concerned.

In quantitative terms the scattered intensity may be written as:

$$I_{s'} = C I_o N \sigma f(T) \Omega . \prime \tag{1}$$

where C is a calibration constant of the system, N is the number of scatterers, σ is the equivalent scattering cross-section, Ω solid angle, and $\prime$ the scattering length.

Equation 1 written in terms of the scattered signal photons, becomes:

$$n_s = \frac{E_o N \sigma . \ell \Omega \tau_o}{E_p} \tag{2}$$

and in terms of a voltage signal

$$V_s = \frac{E_o N \sigma . \ell . \Omega . \tau_o \eta_q . G.E.R}{E_p . t.} \tag{3}$$

where E_o is the incident laser energy, τ_o and η_q the optical and quantum efficiencies respectively, G the gain of the photomultiplier, e the electron charge, R the load resistance, E_p the energy of the scattered photon, and t_p the laser pulse duration. In thermal equilibrium, the ratio of the Stokes to anti-Stokes intensity can provide the temperature according to the equation:

$$T = \frac{h \nu c}{k} \left[\ln \frac{I_s}{I_A} + 4 \ln \left(\frac{\nu_o + \nu}{\nu_o - \nu} \right) \right] \tag{4}$$

It is clear from the above that in principle it is possible using Raman scattering to obtain instantaneously and simultaneously the temperature and specie concentration in a mixture of gases. The former because the Raman transitions take place in a time of the order of fractions of pico-seconds, the latter, because both the Stokes and anti-stokes intensities may be obtained simultaneously.

A major drawback of the Raman diagnostic technique, is the extremely small equivalent scattering cross-section, which depending on the incident laser frequency and specie of interest may vary from $10^{-31} cm^2/sr$ to $10^{-48} cm^2/sr$. This low scattering cross-section forces not only a minimum limit on the resolvability of specie concentration, which is relatively high, and may also limit the resolution of small fluctuations in concentration in a flow field.

A recent new development in Raman Spectroscopy may, in some cases, improve these conditions. This new development, known as CARS (Coherent Anti-Stokes Raman Scattering), has been shown to have an equivalent Raman scattering cross-section of up to 6 orders of magnitude higher than the spontaneous Raman Effect. Consequently, specie concentration levels, of several orders of magnitude lower than before can be expected to be resolvable.

The CARS Effect

The coherent Anti-Stokes Raman Scattering Effect or CARS[11],[12] may be qualitatively described as a process by which a *photon* ν, interacts with a tunable photon, ν_2 (Stokes photon of the given specie of interest) through the third order nonlinear susceptibility to generate a polarization component of the Anti-Stokes frequency $\nu_3 = 2\nu, -\nu_2$. This is diagrammatically represented[2] in Fig. 2.

Quantitatively the Anti-Stokes scattered power can be shown to be represented by:

$$P_{as} = \frac{2.77.10^{-3}}{n_{as}^4 \lambda_{as}^2} \left[\frac{\prime_{coh}}{A} \right]^2 \times \tag{5}$$
$$\lceil N \chi \rceil^2 P_L^2 P_s$$

where P_{as}, P_L, P_s are the powers of the Anti-Stokes, incident laser, and Stokes radiation respectively, $\prime_{coh}$ is the coherence length in cm, n_{as} is the index of refraction at the Anti-Stokes frequency, A is the interaction crossectional area in cm^2, λ_{as} is the Anti-Stokes wavelength in cm and χ is the Raman Susceptibility.

The coherence length $\prime_{coh}$ defined as $\pi/\Delta k$ where $\wedge k = 2k, -k_2 -k_3$ may be written as:

2

$$'_{coh} = \frac{\pi c}{\nu_{vibr}^2}\left[2\ \frac{\partial n}{\partial \nu} + \cancel{\nu_L \frac{\partial^2 n}{\partial \nu}} + \nu_L\ \frac{\partial^2 n}{\partial \nu^2}\right] \quad (6)$$

and the Raman Susceptibility χ may be expressed as

$$\chi = \frac{2\pi^2 c^4}{h\omega_L \omega_s^3 \Gamma_R}\ \frac{d\sigma}{d\Omega} \quad (7)$$

It is evident from Eq. (5) that unlike the relation of Eq. (1), the specie concentration is not linearly related to the scattered radiation. This negative feature of CARS is offset by the much higher equivalent scattering cross-section (several orders of magnitude), than that of the spontaneous Raman Effect. The magnitude of the equivalent scattering cross-section, however, cannot be the only criterion by which the above diagnostic techniques may be evaluated. Other features must be considered. For example: the spontaneous Raman Effect permits the measurement of many species[13] which may be present in a given system, simultaneously using a single primary laser. This is not possible with the CARS diagnostic method. The spontaneous Raman diagnostics is single ended[14]. That is, the transmitter and receiver may use the same optics or may be located in proximity to each other. This is not possible with CARS except by using remotely located reflecting mirrors. CARS, on the other hand, due to its coherent high intensity beam, may be advantageous in systems with high background illumination, fluorescence, or radiation which may, in some cases, make measurements with the spontaneous Raman Effect impossible.

The L.D.V.

The Laser Doppler Velocitymeter[14,15,16], as is well known is based on The Doppler principle. Thus, if a small volume in a flowfield (Fig. 3) is illuminated by a laser beam, the frequency of the laser light scattered by moving particles in the volume, will appear to a stationery observer as shifted in frequency from the incident beam. This shift in frequency being proportional to the velocity of the scattering particle. The L.D.V. has been developed in the last several years to such an extent, that is now becoming a standard basic instrument in most laboratories dealing with flowfield phonomena. A particularly useful application of the L.D.V. is in acquiring information on turbulent parameters in flowfields and combustions[17]. In a one dimensional Doppler system the mean velocity may be represented by:

$$\bar{u} = \frac{\lambda_o \sum_i f_i d_i}{N 2\sin^{\theta}/2} \quad (8)$$

and the RMS value of turbulence for $u' = u - \bar{u}$ by:

$$(u'^2)^{\frac{1}{2}} = \frac{\lambda_o}{2\sin^{\theta}/2}\left[\frac{\sum\limits_i^N f_i(d_i)^2}{N-1} - \frac{(\sum\limits_i^N f_i d_i)^2}{N-1}\right]^{\frac{1}{2}} \quad (9)$$

Experimental Apparatus

The experimental apparatus used in this work consisted of 4 basic systems:

a) The basic Raman System used to obtain temperature and concentrations of a flow field or flame.
b) The L.D.V. System for velocity and turbulent intensity.
c) The CARS System to obtain small traces of unburned methane in an air methane flame.
d) The jet and combustion system.

A diagramatic representation of the complete experimental apparatus is shown in Figs. 3, 4 and 5 and some photographic views in Figs. 6 and 7. A full description of the experimental apparatus is given in Refs. 7, 13. The basic components of the apparatus are indicated in the schematic diagrams.

A common component in the above experimental arrangements is the data processing system, consisting of a data acquisition, storage and computing facility. This system allows the acquisition of a large amount of experimental data, store the raw data, and subsequently retrieve, analyze and present in a proper manner. This apparatus permits the acquisition of data concerning concentration and temperature of several species in the flow field as well as the velocity of the flow simultaneously.

Experimental Results and Discussion

Using the above experimental facility, specie concentration, temperature, velocity and turbulent intensity profiles have been obtained in a flame simultaneously. Some sample profiles are shown in the next several figures. Thus Fig. 8 presents a normalized velocity profile and corresponding turbulence intensity in an air methane flame at $x/D=5.2$. Fig. 9 is a sample normalized concentration profile of N_2 in the same flame at the same x/D station. The corresponding fluctuation intensity obtained from the N_2 concentration data and processed similarly as the velocity data is shown in the same figure.

A similar profile of CO_2 concentration in the same flame at the same station and at the same time is shown in Fig. 10 with the corresponding concentration fluctuation intensity. The temperature profiles as obtained from N_2 and CO_2 and their corresponding fluctuation intensities are shown in Fig. 11 and 12. Fig. 13 and Fig. 14 present the coherent anti-stokes Raman intensities as obtained using the system shown in Fig. 4 and Fig. 7, for methane and hydrogen as a function of pressure.

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Using the same CARS system and substituting a flame for the pressure cell, an attempt has been made to obtain concentration of unburned methane in an air methane flame. Several points representing the concentration of residual unburned methane were obtained. The data at the moment are of a preliminary nature at a point in the flame. An attempt to obtain concentration measurements of methane, using the spontaneous Raman effect and the available laser under the same flame conditions proved unsuccessful due to the small amount of unburned methane left in the flame. This result points out the usefulness of CARS under adverse conditions of noise and minimal amounts of the species of interest in a given system.

From the concentration data as shown in Fig. 9 and 10 a parameter proportional to the so called chemical mixedness term[5] may be found. This parameter of importance in turbulence modeling may be obtained here because of the fact that the concentrations of the individual species are obtained simultaenously when using the single pulse Raman scattering diagnostic method. For the 2 examples of specie concentrations in a flame as shown in Fig. 9 and 10, this parameter is shown in Fig. 15.

Returning to the velocity, concentration, temperature and turbulence intensity measurements, it is evident that the L.D.V. and the Spontaneous Raman diagnostic system are capable of providing most of the important information in a flow field. In addition, a first attempt has been made here to extract a parameter which can be related to the mixedness which is most useful in turbulence modeling.

Acknowledgment

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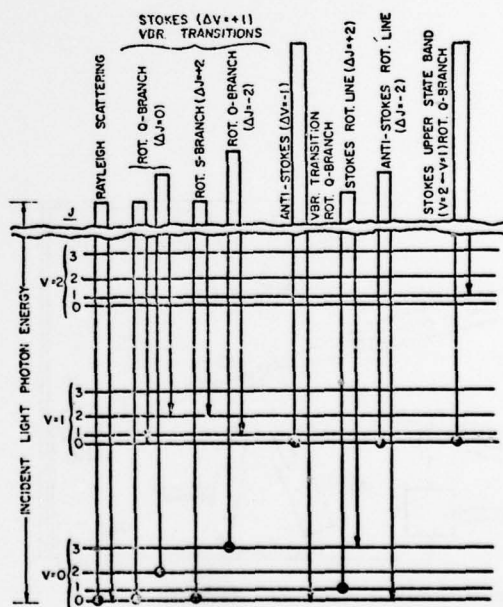
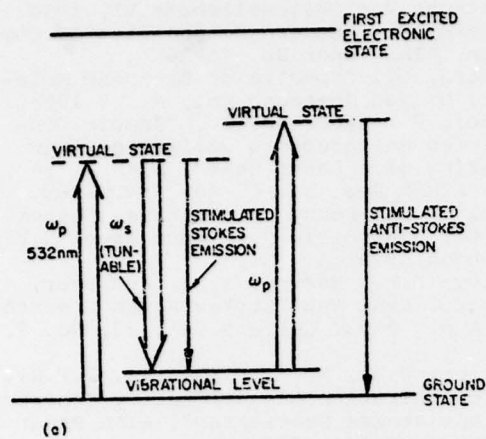FIG. I SCHEMATIC DIAGRAM OF MOLECULAR TRANSITION (REF. 10)

FIRST EXCITED
ELECTRONIC
STATE

VIRTUAL STATE

VIRTUAL STATE

ω_p
532nm

ω_s
(TUN-ABLE)

STIMULATED
STOKES
EMISSION

ω_p

STIMULATED
ANTI-STOKES
EMISSION

VIBRATIONAL LEVEL

GROUND
STATE

(a)

$|\vec{k}| = \dfrac{\omega n}{c}$

$2\omega_1 - \omega_2 = \omega_3$

$2\vec{k}_1 = \vec{k}_2 + \vec{k}_3$

FIG. 2 ENERGY LEVEL AND PHASE MATCHING
DIAGRAM (REF. II)

FIG. 4 SCHEMATIC DIAGRAM OF THE COHERENT RAMAN ANTI-
STOKES SCATTERING APPARATUS

MONOCHROMATOR
AND PMT

DATA ACQUISITION
AND PROCESSING

REFERENCE PRESSURE
CELL

PIN
PHOTODIODE

RUBY
LASER

IRIS
AND
LENS

SRS
CELL

FILTER
AND LENS

TEST
CHAMBER

MONOCHROMATOR
AND PMT

PRE-AMPLIFIER LINEAR GATE

PRE-AMPLIFIER LINEAR GATE

PRE-AMPLIFIER LINEAR GATE

PRE-AMPLIFIER LINEAR GATE

PRE-AMPLIFIER LINEAR GATE

DELAY LINE GATE GENERATOR

MULTIPLEXER
AND A TO D
CONVERTER

PDP
MINICOMPUTER

TELE-
PRINTER

RECORDER

L.D.V.
SYSTEM

FIG. 5 DATA ACQUISITION SYSTEM

STOKES
RECEIVER

ANTI-STOKES
RECEIVER

HE-NE LASER

JET

RUBY LASER

MONITORING
PHOTODIODE

STOKES
RECEIVER

ANTI-STOKES
RECEIVER

L.D.V.
RECEIVER

DATA
ACQUISITION
AND
REDUCTION

FIG. 3 BLOCK DIAGRAM OF EXPERIMENTAL APPARATUS
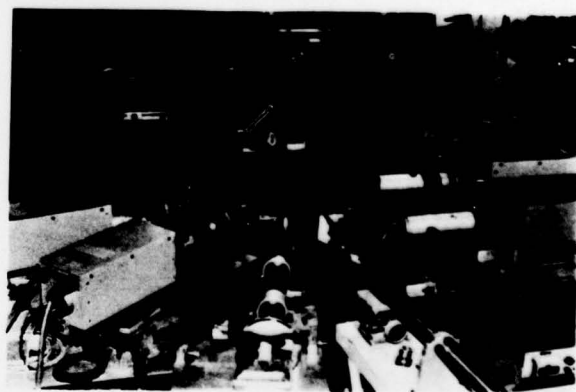
FIG. 6 PHOTOGRAPHIC VIEW OF RAMAN
AND L D V APPARATUS

5

FIG. 7   PHOTOGRAPHIC VIEW OF COHERENT
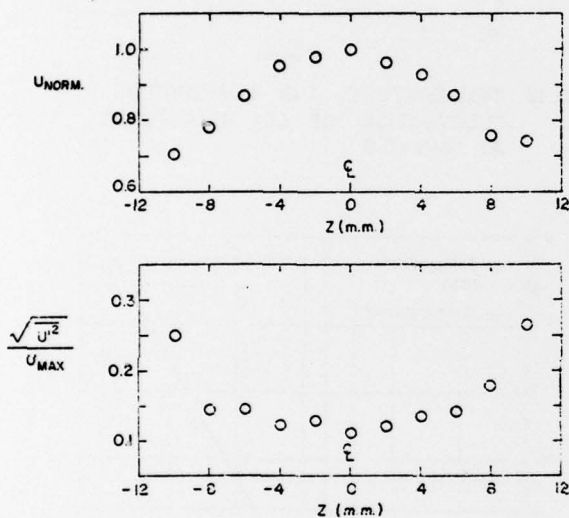ANTI-STOKES SCATTERING APPARATUS

FIG. 8   VELOCITY AND TURBULENT INTENSITY
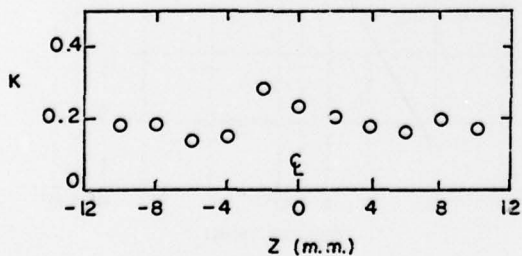PROFILE IN A FLAME AT X/D = 5.2

FIG. 15   THE "MIXEDNESS" PARAMETER
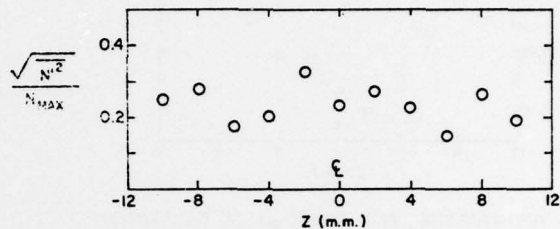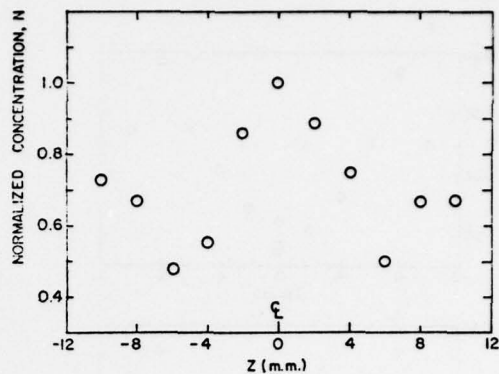K OF N_2 AND CO_2 IN AN
AIR METHANE FLAME

FIG. 9   NORMALIZED CONCENTRATION OF N_2 IN A
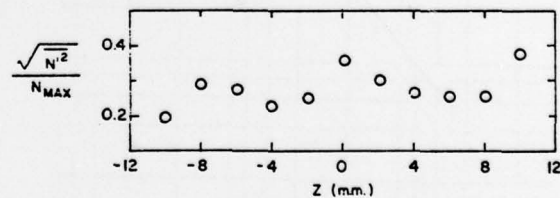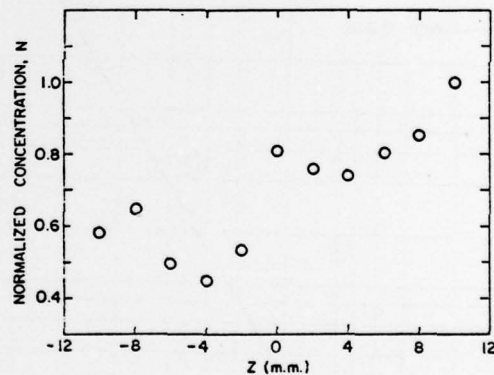FLAME AT X/D = 5.2 AND THE
CONCENTRATION FLUCTUATION

FIG. 10   NORMALIZED CONCENTRATION OF CO_2 IN
A FLAME AT X/D = 5.2 AND THE
CONCENTRATION FLUCTUATION
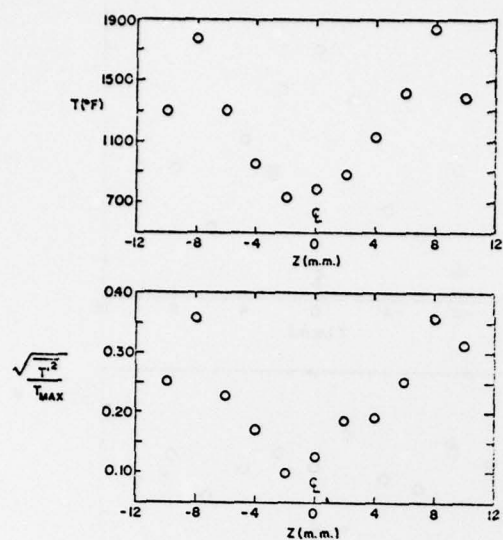
6

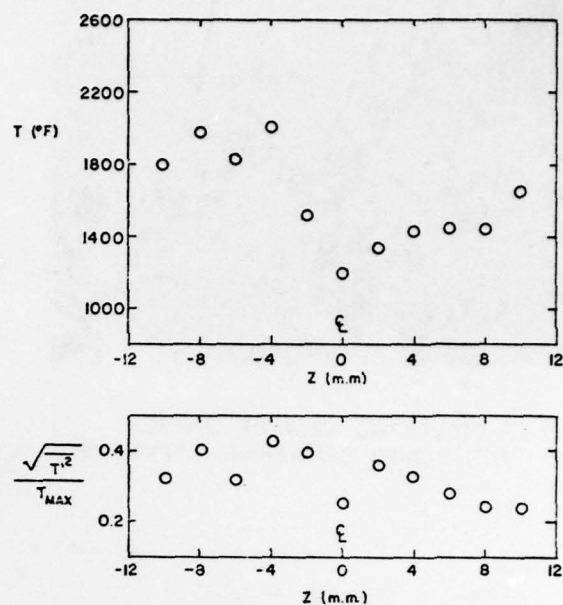FIG.11 TEMPERATURE AND TEMPERATURE FLUCTUATION
PROFILE IN A FLAME AT X/D =5.2 (N₂)

FIG. 12 TEMPERATURE AND TEMPERATURE
FLUCTUATION OF CO_2 IN A FLAME
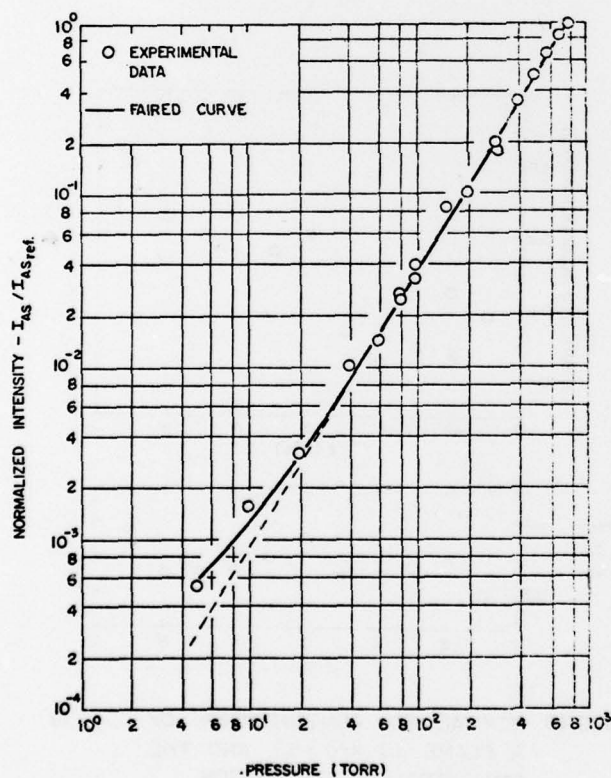AT X/D =5.2

FIG. 13 MEASURED COHERENT RAMAN ANTI-
STOKES INTENSITY OF METHANE (CH_4)
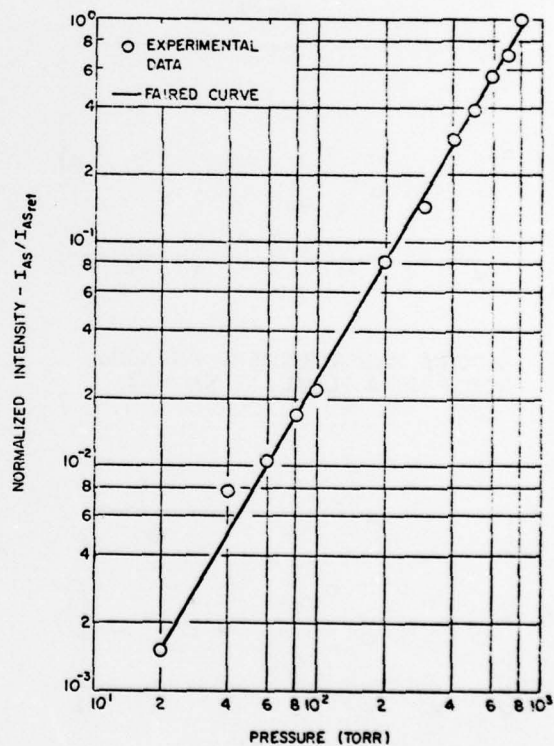AS A FUNCTION OF PRESSURE

FIG. 14 MEASURED COHERENT RAMAN ANTI-
STOKES INTENSITY OF HYDROGEN (H_2)
AS A FUNCTION OF PRESSURE

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19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

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Combustion
Raman Scattering
Velocity
Temperature

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The recently developed Laser Raman and Laser Doppler techniques may be ideally suited for the diagnostics of combustion. Both techniques are nonintrusive and essentially supplementary. However, under certain conditions the spontaneous Raman diagnostics may fail, due to excessive noise, unwanted fluorescence and other sources of interference. In order to alleviate these difficulties, an attempt has been made to use the CARS diagnostic
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20. ABSTRACT (Cont'd)

method. In this paper, after a review of the above-mentioned diagnostic techniques, some experimental results, and some data processing methods are discussed, which permit the extraction of turbulent information from spontaneous Raman scattering. These are compared to turbulent data as obtained from L.D.V.